Numerical And Experimental Analysis Of A New Conception Of Road Restraint Systems

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SYNOPSIS

Today, differently from other countries, the use of restraint systems for hazardous singularities on Italian roads is not widespread. This lack is mainly due to a missing design consciousness of the roads passive safety importance and to a deficiency in terms of safety analysis and safety review procedures. Furthermore, present Italian Standards does not support the engineer with satisfactory guidelines for restraint systems design and positioning and in addition, difficulties for placement and repairing are not unusual. The increasing number of accidents involving roads singularities like cusps, bridge piers, pillars, tunnel portals and so along, is sufficient to highlight the scale of this issue.

In this paper, moving from a wide analysis of existing restraint systems classified by either their geometry, or construction characteristics and absorbing energies related with their constitutive materials, a new type of device is presented. If existing systems are mainly built with a steel confining structure filled with stress absorbing elements performing a plastic behaviour, the proposed one involves the use of expanded clay, opportunely graded, bound with high strength thermoplastic polymers. These device present some advantages, like reduced number of pavement anchoring, high energy absorption, low costs and easy replacement.

Physical-mechanical characteristics of the constitutive material have been determined as first step, by means of laboratory tests conducted on reduced scale specimens. Step two needed standardized impacts numerical analysis made with a specific kineto-dynamic software able to reproduce different impact scenarios. An optimal system configuration has been identified in terms of cushions number, shape and position as well as material characteristics. The evaluation was conducted with regard to the vehicle and attenuator behaviour during the event and to the values of the ASI, THIV and PHD parameters.

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INTRODUCTION

According to 2002 statistics, in Italy, more than 8000 people died for traumas due to road accidents. 25 out of 100 died as consequence of vehicle impacts with hazardous road boundary elements or singular elements (ISTAT-ACI, 2003). In the stream of drastically reducing the number of victims and negative events, the need of enhanced passive road restraint system is arising. Therefore, efforts have to be made to develop safer and cost effective devices and to spread their use. Among them crash cushions can be numbered as black-spot safety systems. Their function is to prevent uncontrolled vehicles impacts against rigid obstacles or similar elements within their trajectory (see figure 1).

Figure 1: Some examples of crash cushions for hazardous points

Well designed systems are able to absorb most of the impact energy, producing a gradual vehicle stop with no excessive deformations and reducing passengers injuries for the reduced levels of deceleration.
Protected elements can be for example:

- free-edges of road structures (bridges piles, viaducts, retaining walls, etc.);
- lighting poles and signals posts;
- cusps and zones of needle diversion;
- safety barrier terminals either central or lateral;
- tunnel portals;
- bumper of highway toll-gates;
- strategic spots in road construction sites;
- others.

Scheduled repairing and parts substitutions are the major limits to their use and sometimes the driver's sight distance may be reduced. Nevertheless, the contribution of these systems to road passive safety is undoubted and the improvement of infrastructure intrinsic safety is significant. A Norwegian research study highlighted that crash cushions reduce the severity of accidents as well as the accidental rate, as lateral restraint systems do (Elvik, 1995).
For evaluating their safety performances crash devices are usually tested by means of full-scale impact tests. Tests are expensive and cushion systems design becomes very complicated, especially because of difficulties when it comes to set up instrumentations for data acquisition (Dondi and Simone, 1997).
From this point of view, a full series of numerical simulations of vehicle-cushion impacts are useful means for time and money saving and well support the full-scale testing (Dondi and Simone, 2000, 2001). Modelling with finite elements enables the engineer to analyse various impact scenarios of the same crash in a short time. Simulations provides with the capabilities of estimating and forecasting the crash cushions performance on the road. The most detrimental event for the vehicle passengers can be investigated and several useful information, not easily recordable on real test, can be gained: e.g. critical points stress distributions on crash cushions and vehicle parts (Sicking and Mak, 2001).
Firstly, in this paper, a brief review of the existing Standards and the main types of crash cushions currently employed on world roads are proposed. Then, a new Conception of Road Restraint System made with expanded clay materials is described. The performance and the behaviour of the designed system have been investigated and validated with numerical simulations of light car longitudinal impacts by means of the well known LS-DYNA3D software (Whirley and Engelmann, 1993).

CRASH CUSHIONS TESTING GUIDELINES

The first exhaustive specifications and Standards on crash cushions have been released by the Transportation Research Board within the National Cooperative Highway Research Program (Michie, 1981). The reference report is the NCHRP 350 *"Recommended Procedures for the Safety Performance Evaluation of Highway Features"* (Ross et al. 1993), where guidelines are reported for evaluating safety performances of traffic barrier systems, end treatments, crash cushions, breakaway devices, truck-mounted attenuators and other hardware. A large range of crash tests for each system category is given as well as indications for their performance evaluation in terms of:

- structural adequacy;
- occupant risk;
- after-collision vehicle trajectory.

As far as structural adequacy is concerned, the system is assessed on the basis of its capability in restraining and redirecting the impacting vehicle in safe conditions, with no tip-over risks.
Occupants exposure is determined either by means of conventional reference indexes like ASI, PHD and THIV and verifying that no parts from the system are penetrating the cockpit.
Eventually, possible interferences of the post-impact vehicle trajectory and road traffic are taken into account as well as the likelihood of impacting other obstacles.
Crash cushions are classified with 3 performance levels or Test Levels, according to the test vehicle impacting speed :

- TL1 for v = 50 km/h
- TL2 for v = 70 km/h
- TL3 for v = 100 km/h.

TL1 class systems assure a minimum restraint energy value, whereas class TL2 and TL3 ones give higher performances.
Each class is related with a specific series of tests which differ from:

- type of system (redirective or non-redirective, gating or non-gating)
- type of test vehicle (car, pick up, truck, etc.)
- impact position (front, lateral, etc.)
- impact angle.

The Test Level class for each system is determined on the basis of the positive tests succession.

Italian Standards

Italian decree D.M. LL. PP. 3/6/98 n. 223/3 "Aggiornamento delle istruzioni tecniche per la progettazione e l'omologazione delle barriere stradali di sicurezza e delle prescrizioni tecniche per le prove ai fini dell'omologazione" introduced in Italy the concept of crash cushions for the first time. The decree specifies the design and operate criteria for crash cushions systems and for end treatments devices with the aim of containing the impact energies and the negative effects on the occupants.
Differently from U.S. specifications, the Italian Standard distinguishes only between redirective (R) and non-redirective (NR) systems on the basis of their behaviour in a lateral impact: the gating or non-gating behaviour is not taken into account. Crash cushions are classified by means of the Restraint Level Lc, conventionally defined as the vehicle kinetic energy before the impact, worked out with the same equation used for barriers.
The decree defines two classes of cushions:
TC1: cushions with Lc = 320 kJ
TC2: cushions with Lc = 500 kJ
ASI index is then conventionally defined for classifying accident severity. The impact effect on seated and belted occupants is considered for this purpose. PHD and THIV index are not measured.
Standard System complying is dependant on the positive result of full-scale impact tests at the end of which the following conditions should be satisfied:

- front and lateral (if required) impacting vehicle control, with no visible jumping;
- no parts from the system penetrating the cockpit and no cockpit deformations that may cause serious injuries to occupants;
- no large size parts detaching from the collided system;
- no vehicle penetration in the front surface of the obstacle after deformation;
- normal vehicle trim when moving with admission of moderate yaw, rolling and pitching;
- for redirective systems: exit trajectory within a line parallel to the impacting side and distant 4 m on the cushion terminal point normal;

For verifying the Restraint Level Lc, crash tests shall be performed in accordance with specifications given in table 1.

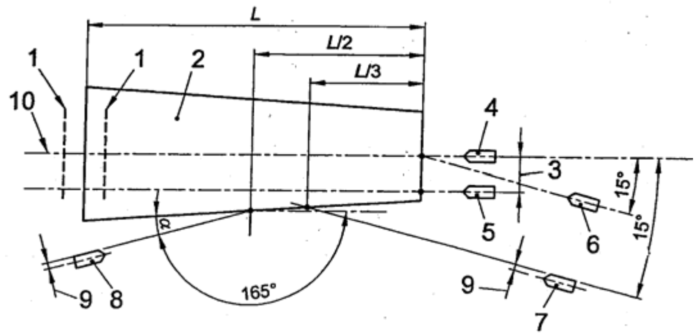
Table 1: Crash cushions – crash tests criteria for vehicles (D.M. LL. PP. n. 223/3, 3/6/98)

Class	Type	Speed(km/h)	Impact Angle (°)	Total Vehicle Mass (kg)	Vehicle Type
TC1	R/NR	80	90	1300	Car
	R/NR*	80	90	900	
	R**	80	15	1300	
TC2	R/NR	100	90	1300	Car
	R/NR*	100	90	900	
	R**	100	15	1300	

(*) This test represents a frontal impact on an axis distant ¼ of the vehicle width from the system axis.
(**) This test represents a lateral impact at 1/3 of the total system length and should be performed on (R) Systems.

In January 2002 the European Standard was acquired in Italy as UNI EN 1317-3 "Barriere di sicurezza stradali. Classi di prestazione, criteri di accettabilità basati sulla prova di impatto e metodi di prova per attenuatori d'urto", and became a national Standard. Its objective is to match all the related national specifications.
In this document requirements for crash cushions systems performances during impacts are specified as well as the performance classes and the acceptance criteria for crash tests. Like in the described decree a typological distinction between redirective and non-redirective systems is proposed and no mention is given for gating and non-gating ones.
The classification is based on the energy absorption capacity calculated with specific full-scale tests that enables the engineer to verify the cushion behaviour for different kind of impacts (see table 2 and figure 2).
Crash tests results define their acceptability with regards to:

- restraint level;
- vehicle impact severity;
- vehicle trajectory;
- production and distribution of debris from the vehicle and the system;
- system deformation.



Legend:
1. alternatives for obstacle frontal side location
2. crash cushion
3. ¼ distance for test n°2
4. test n°1
5. test n°2
6. test n°3
7. test n°4
8. test n°5
9. ½ vehicle width
10. cushion longitudinal axis

Figure 2: Crash tests vehicle trajectories (UNI EN 1317-3)

Following the steps of the NCHRP Report 350, four performance levels are defined on the basis of the vehicle-system impact speed (50, 80/1- 80, 100, 110). At each level a specific series of impact tests is given: the performance class is determined with the number of successful tests.
The impact Severity Index is evaluated by means of the ASI index: if the parameter is less then or equal to 1.0, the system is classified A, if the parameter is less then or equal to 1.4 it falls in Class B.
In both cases it shall be:

- THIV ≤ 44 km/h in front impacts;
- THIV ≤ 33 km/h in lateral impacts;
- PHD ≤ 20g, where g = 9.8 m/s^2.

Specific limits are imposed for the post-impact vehicle trajectory according to the performed test. Systems are divided into 5 Classes (Z1, Z2, Z3, Z4, Z5) with relation to the distance of the vehicle from the cushion at the end of testing.
Finally, crash cushions are divided up into 8 classes on the basis of the maximum permanent displacement of the system after the event (D1, D2, D3, D4, D5, D6, D7, D8).
The Standard requires also that no parts from the system may penetrate the cockpit or obstruct the adjacent traffic; moreover, no elements with mass more or equal to 2 kg shall completely detach from the system.
Similarly to the U.S. standards, the European Standard suggests an exhaustive and complete systems classification, taking into account, in performance evaluation, the three parameters quoted in the NCHRP Report 350: structural adequacy, occupant risk and after-collision vehicle trajectory.
On the contrary the 3/6/98 decree does not request specific parameters for assessing the post-impact vehicle trajectory and, moreover, leaves to the only ASI index the measurement of the occupant risks.

A serious deficiency, present in all the described Standards, is the absence of two-wheels vehicles for performance evaluation crash tests. For these vehicles the impact dynamic is very different from the one of cars and trucks, in particular, as stability and trajectory after collision are concerned, the occupant risks are much higher.

Table 2: Crash cushions - crash tests criteria for vehicles (UNI EN 1317-3)

Test[1)]	Impact	Total Vehicle Mass (kg)	Speed (km/h)	Figure 1 Test n°
TC 1.1.50 TC 1.1.80 TC 1.1.100	Frontal, centred, 0°	900 900 900	50 80 100	1
TC 1.2.80 TC 1.2.100		1300 1300	80 100	1
TC 1.3.110		1500	110	1
TC 2.1.80 TC 2.1.100	Frontal, ¼ vehicle axis distance	900[2)] 900	80 100	2
TC 3.2.80 TC 3.2.100 TC 3.3.110	Frontal, at 15°	1300 1300 1500	80 100 110	3
TC 4.2.50 TC 4.2.80 TC 4.2.100 TC 4.3.110	Lateral, at 15°	1300 1300 1300 1500	50 80 100 110	4
TC 5.2.80 TC 5.2.100 TC 5.3.110	Lateral, a 165°	1300 1300 1500	80 100 110	5

1) Test notation as given:
TC **1** **2** **80**
Crash Cushion Test Impact Vehicle Mass Impact Speed
2) For this test dummy shall be placed at the most faraway distance from system axis.
Note 1 For Vehicle Specifications and tolerances refer to EN 1317-1.
Note 2 Test 5 is not performed for a non parallel shaped crash cushion when in the impact point, the α angle between the vehicle trajectory and the internal cushion side is less than 5°.

Finally, it is necessary to highlight how the present Italian and European Standards from one hand give sufficient test methods for the performance evaluation of crash cushions, but from the other hand do not specify design criteria or location criteria, leaving to the engineer the choice.

GENERAL CRASH CUSHIONS TYPOLOGIES

Crash cushions have been introduced in U.S., where they still have the largest diffusion, at the end of the 70's . More than 20000 systems are placed on U.S. roads, against the few hundreds placed in Europe.
The very first experimental models consisted of cylindrical elements filled with water or concrete mixtures made with lightweight vermiculite and generally not provided with lateral restraint systems (Casey, 2002).
At the state of the art, crash cushions can be divided into several typologies on the basis of:

- working mechanism;
- redirective capacity;
- gate-ability;
- dissipating materials.

If referring to the working mechanism two classes are defined:

- kinetic attenuators;
- inertial attenuators.

Here follows their description.

Kinetic Attenuators

These devices act absorbing the vehicle kinetic energy transferring it to the loose material of the system which is deformable, compressible or can be minced. They are generally anchored to a rigid element or to the shielded obstacle. Generally, their redirective capacity is fair and they permit the vehicle trajectory to be corrected with lateral impact angles up to 20° similarly to a safety barrier.

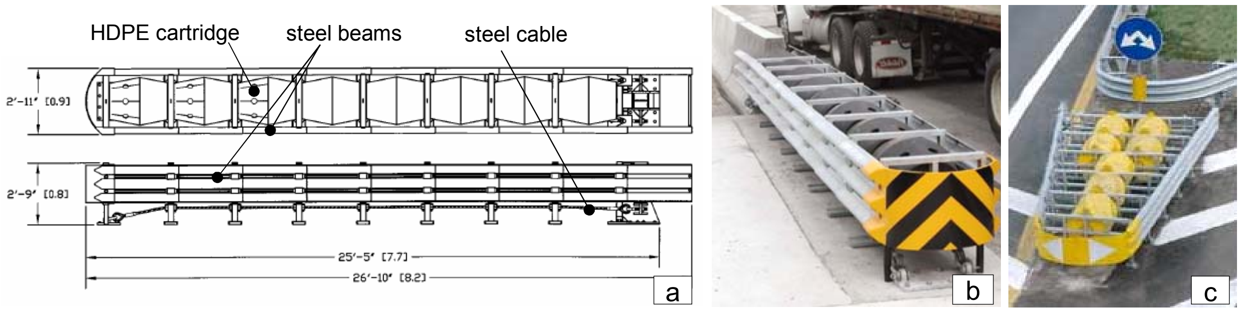


Figure 3: Examples of kinetic attenuators redirective and non-gating.

Figures 3.a and 3.b report an example of kinetic attenuator which is also redirective and non-gating. It is useful for shielding carriageway obstacles (piles of bridges, central barrier terminals, etc.). The energy dissipation is given by the compression of cave double-conic elements made with HDPE or HMW (High Molecular Weight Polyethylene), placed within a steel frame and anchored longitudinally with a couple of steel cables. During the impact, the triple wave lateral blades slip one on the other like a telescope and enable the compression of the central elements. In case of frontal impact it is generally sufficient the substitution of the broken central elements and of the front nose of the system.
Some other similar attenuators exist and are made of element of different shape and materials depending on the producing factory, but the working principle is the same and the energy is dissipated by means of the compression of frame anchored parts.
The system in figure 3.c works in the same way, but is typically mounted in front of cusps and lateral obstacles.
All the described devices are classified as TL3 according to NCHRP report 350, hence they can safely absorb vehicle impacts up to 20 kN weigh and at a maximum speed of 100 km/h.
A fair redirective capacity is offered also by attenuators made with HDPE cylinders. These cylinders are placed in different ways according to the actual case characteristics (see figure 4) and generally enable the vehicle to be redirected progressively in the carriageway after the impact. The advantages of these solutions are basically the low installation and substitution costs, the easiness of employment and their ability in conserving the 80-90% of the original shape as well as their strength characteristics after the impact.
If anchoring cables are used (figure 4.a), a performance class TL3 can be achieved; if they are simply aligned in front of a singular spot (figure 4.b) the TL1 test is generally fulfilled and they assure the containment of 20 kN weight vehicles impacting at a maximum 50 km/h speed. Finally, as cushion wall, they are anchored to the protected wall and can guarantee a TL2 level (vehicles up to 20 kN impacting at 70 km/h).

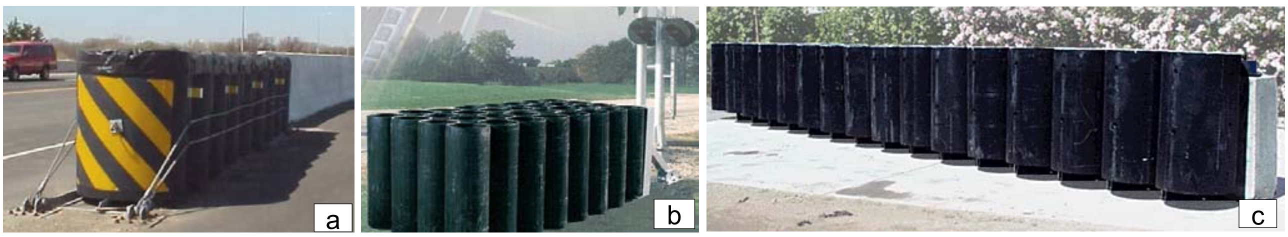


Figure 4: HPDE Cylindrical kinetic attenuators a) as end terminal, b) singular spot shielding, c) as cushion wall

Figure 5 shows some examples of non-gating kinetic attenuators with limited redirective capacity in the case of lateral collision. This is mainly due either to the absence of retaining frames or cables and to the limited elastic properties of the material.
The system of figure 5.a is built with a series of at least 4 poorly cemented expanded clay blocks (monogranular grading 8/12 mm nominal size). These blocks are contained in a high strength nonwoven geosynthetic together with a rubber protection cloth made of PVC and neoprene. The last protection is mainly placed to inhibit the loss of debris after the impact. Blocks are 1.2 m square base and 1.0 m height and are opportunely shaped with cylindrical holes (0.15 m diameter) that further reduce their stiffness. There is also a steel cable that keeps the blocks together and aligned during frontal impact events.
Full-scale crash tests, performed with reference to the specification of D.M. LL. PP. n. 223/3-98 (see table 1) classified this system as a TC1.

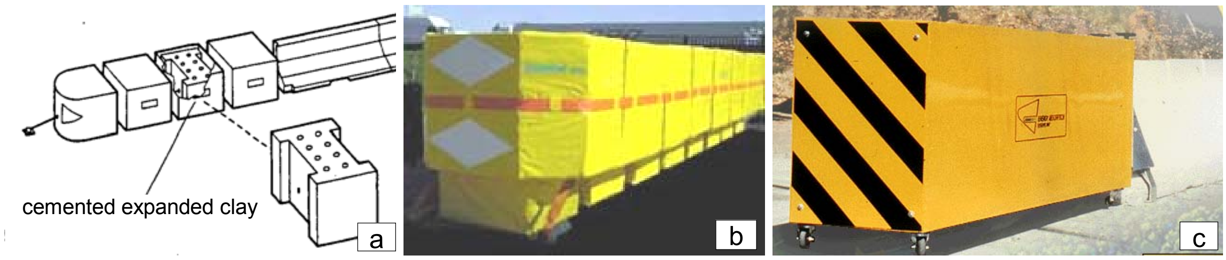


Figure 5: Examples of kinetic attenuators: non-redirective and non-gating

An alternative solution is represented by honey-comb modular attenuators made with HDPE (figure 5.b). The modules are linked together by means of two geosynthetic belts and placed on a base-guide that is anchored either on the ground and to a rigid rear element that permits to dissipate the impact energy. In this case the blocks dimensions are 0.9x0.6x0.85 m and each one weighs 0.25 kN. Satisfactory results have been obtained only in case of frontal impacts at low speeds: consequently these systems can be placed in temporary construction sites, on urban roads and within highways toll-gates.
Finally, figure 5.c shows a box attenuator made of aluminium and folded in an aluminium case that develops large deformations. This device is classified as TL2 and, for its dimensions, is mainly used for shielding carriageway obstacles like New Jersey barriers terminals, bridges piles, tunnel gates, bumpers, etc.

Inertial Attenuators

The working principle of these attenuators is based on the conservation of the quantity of motion. The impacting vehicle kinetic energy is transferred to a mass, generally water or sand, contained into modular elements made of light materials, neither anchored to the ground, nor to any contrast element.
These systems are not always able to properly redirect the vehicle; moreover, they are gating, especially in case of lateral impacts and also require more room if compared to the kinetic systems.
Construction, placing and restoring costs are relatively low if compared to those of kinetic attenuators, therefore these systems are particularly indicated for areas or locations where frequent impacts are expected.
Sand barrels are the main example of inertial attenuators on roads (see figure 6 and 7.a). They are LDPE cylinders systems partially filled with sand and disposed in different number and position configurations on the basis of the expected impact frequency and geometry (figure 6.b). Inside the container a plastic cone is placed to regulate the amount of sand in the cylinder, furthermore this cone assures that the gravity centre is placed at a correct height for absorbing the impact (figure 6.c).

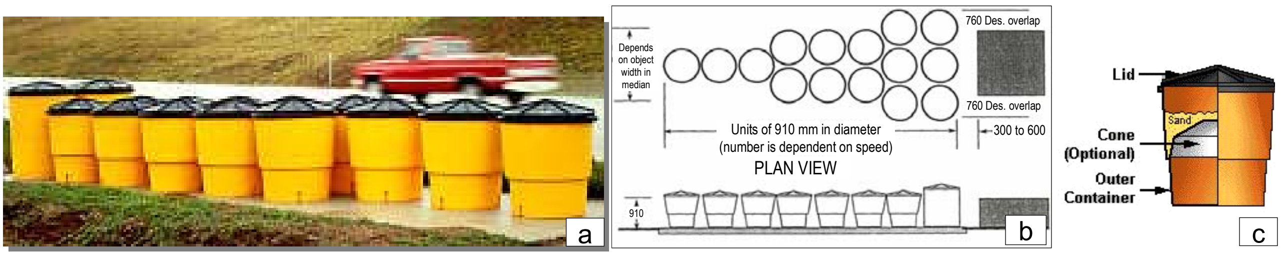


Figure 6: Inertial sand barrels

During impact the barrels system is broken into pieces allowing the loss of sand from the container. The gradual quantity of motion transferred from the vehicle to the plastic and sand system allows a safe and regular stop. Sand barrels are therefore gating, but non redirective systems and according to the amount of sand employed they can guarantee different restraint levels and classified as TL1, TL2 or TL3.
A relatively new conception of inertial attenuator is shown in figure 7.b. This device is specifically designed to absorb frontal impacts and is mainly used in front of New Jersey barrier terminals. It is made of a series of LDPE elements (each weighs 0.5 kN) filled up with about 0.3 m^3 of water. Containers are connected each other and anchored to the barrier with a steel joint. This device is classified as non redirective and gating. The restraint class is determined with full-scale crash tests (see figure 7.c) and results as TL2 for systems with 6 elements and TL3 for systems with 10 elements.

Figure 7: a) Sand barrels, b) inertial end treatment, c) full scale impact test on inertial end treatment

From this analysis some conclusions can be taken:

- kinetic systems are able to redirect the impacting vehicle, generally do not release debris on the road surface and have higher construction and repairing costs if compared to the inertial systems;
- inertial systems can reach the same performance of kinetic systems in terms of restraint levels, but do not have redirective capacity, they are gating and, after an impact, a large amount of debris (plastic, sand, water) need to be swept from the road pavement surface.

A NEW ROADSIDE CRASH CUSHION MODEL IN LIGHTWEIGHT MATERIAL

Experimental analysis

A new type of road restraint system made with lightweight material bound with resins is here proposed as a stationary vehicle impact attenuating device. This system could be specifically used for shielding narrow hazards, for instance concrete middle barrier ends or bridge piles, and could be classified as non gating and, for its shape, potentially redirective. In terms of working mechanism, the proposed system can be classified either as kinetic and as inertial; in fact, if from one hand cushions are made of deformable material that can dissipate energy developing large deformations, from the other hand the cushions are displaced and can translate inside a concrete base guide when impacted.
The performances of the developed crash cushion and of its material have been investigated by means of the well known LS-DYNA3D software used worldwide for dynamic impact events modelling (Miller and Carney, 1997; Reid et al., 2002).
In a first phase, the cushion material was characterised by a set of experimental laboratory tests on different lightweight mixtures. A couple of expanded clay mixtures have been blended for producing several cylindrical specimens (figure 8): three different polymeric resins were used as binders. After a 48 hours curing period, the specimens strength was investigated by means of traditional compression and tensile tests. The basic properties of binders and aggregates are shown in table 3.

Table 3: Properties of binders and expanded clay

Binder	Bulk density (kN/m^3)	Tensile Yield Stress (MPa)	Failure strain (%) (ISO 8339)
Synthetic rubber	12.7	0.10	1000
Acrylic resin	16.5	0.30	150
Silicon resin	12.0	0.80	300
Aggregate	Bulk density (kN/m^3)	Compression Strength (MPa)	Internal friction angle (°)
Expanded clay	6.0	1.2	35

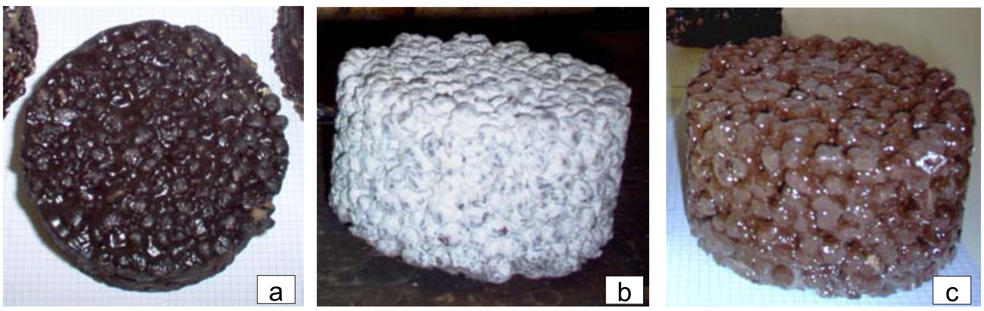


Figure 8: Samples of expanded clay bound with a) elastic rubber, b) acrylic resin, c) silicon resin

The indirect tensile test (ITT – 50 mm/min and 20°C) and the compression test (CT – 10 kg/s and 20°C) were performed for evaluating the mechanical characteristic of the mixtures (figure 9). The mean recorded stress σ versus strain ε curves are represented in figure 10.

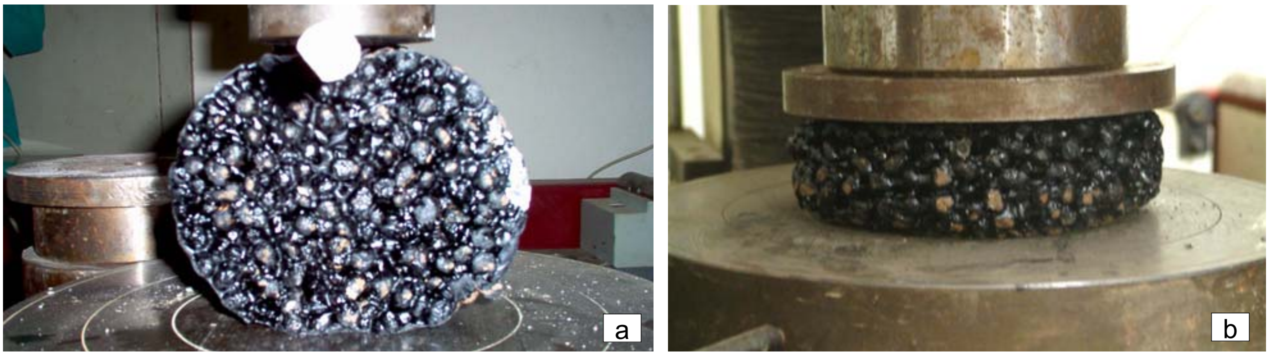


Figure 9: a) Indirect tensile test ITT, b) compression test CT

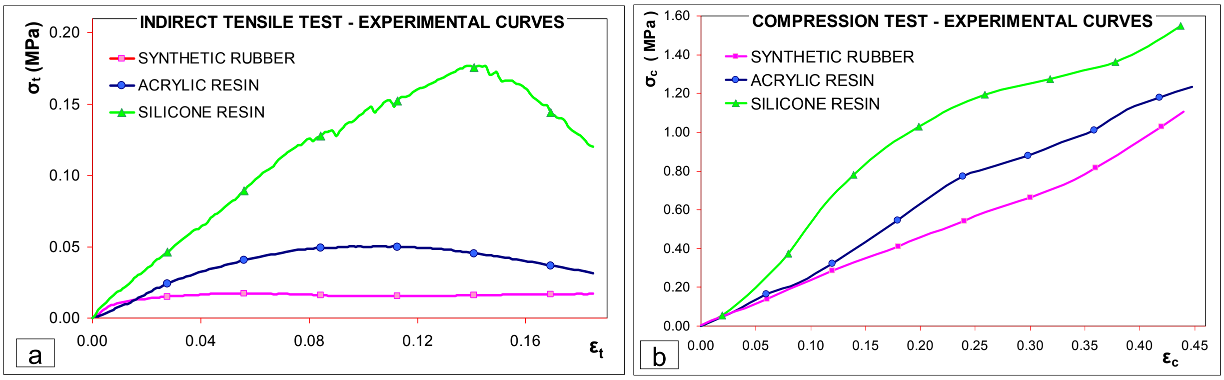


Figure 10: a) ITT experimental σ – ε curves, b) CT experimental σ – ε curves

Tests results shows that:

- the highest mechanical properties are performed by the mixture bound with silicon resin: this is much likely due to the higher adhesion and cohesion characteristics of the binder;
- the mixtures bound with synthetic rubber and acrylic resins present similar characteristics of strength;
- the mixture bound with silicon resin under tensile stresses shows a strength which is more than 3 times higher than the other mixtures;
- the mixture bound with silicon resin under compression stresses shows an elastic behaviour until a critical stress after which the stiffness modulus decreases mostly due to failure within the aggregates which are still well coated by the binder;
- the bulk modulus calculated for the mixture bound with silicon resin is higher than the ones calculated for the other mixtures: this is mainly due to the higher confining properties of the binder that leads to the crushing of the aggregates after the mixture air voids reduction;
- during unloading (not plotted in figure 10) mixtures bound with synthetic rubber and acrylic resins present a smaller elastic recovery than the mixture bound with silicon resin which may offer residual attenuating resources;

From the ITTs the maximum value of tensile stress σ_t for each mixture was recorded, while Young's modulus E were worked out from the CT outputs. Mixtures Poisson's ratios *v*, shear modulus G and bulk modulus K were back-calculated by simulating the compression test using the LS-DYNA3D code (figure 11 and 12.b). The measured and back-calculated properties values for each mixture are shown in table 4.

Table 4: Properties of the experimental mixtures

Binder	Bulk density (kN/m^3)	Max Indirect tensile stress σ_t (MPa)	Young's modulus E (MPa)	Poisson's ratio *v*	Shear modulus G (MPa)	Bulk modulus (MPa)	
						K_1	K_2
Synthetic rubber	6.07	0.017	2.30	0.45	0.60	5.77	2.00
Acrylic resin	6.02	0.051	2.90	0.43	0.80	5.48	2.50
Silicon resin	6.00	0.176	5.29	0.43	1.20	8.17	3.00

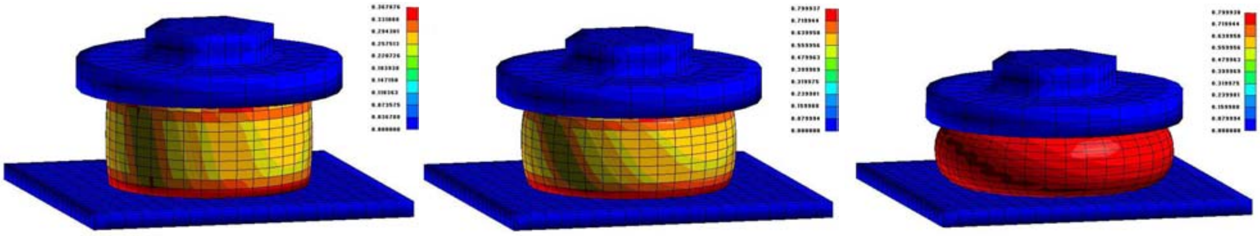


Figure 11: Compression test LS-DYNA3D simulation

Following the experimental phase, each mixture was then numerically modelled with the LS-DYNA3D "Aggregate and Foam" material model, characterized by the general crushable behaviour represented in figure 12.a, where pressures are plotted against volumetric strains (Whirley and Engelmann, 1993). The aim was to reproduce the three mixtures behaviours with a relatively simple algorithm and choose the most reliable model. Figure 12.b shows for each mixture the compressive stress vs. compressive strain comparison between experimental data and LS-DYNA3D simulations data. Silicon resin mixture model was chosen for the following simulations, even though some corrections within the material model were expected. These corrections would be mainly related with the stiffness of the real material and with the fact that crash events are dynamic and laboratory tests (ITT and CT) are not.

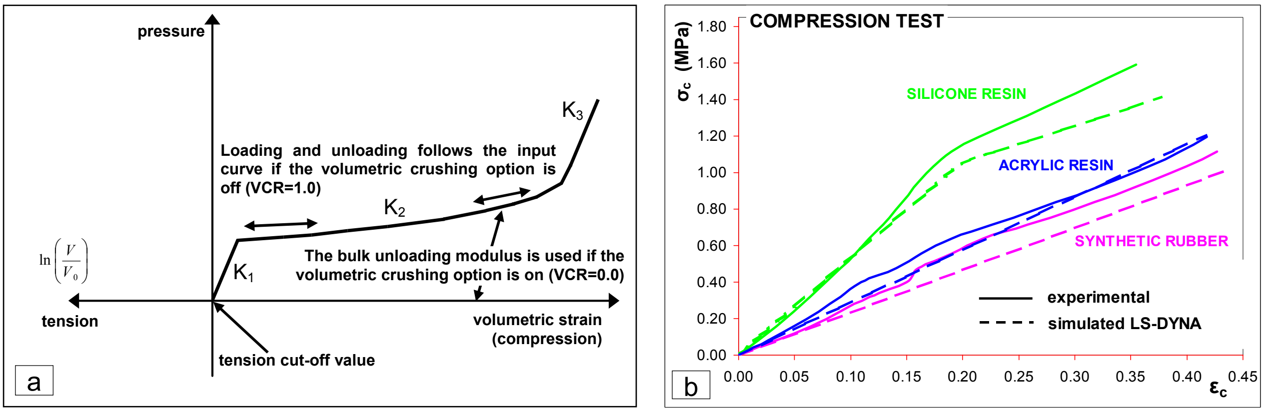


Figure 12: a) Pressure vs. volumetric strain curve for Aggregate and Foam Material Model, b) comparison between experimental data and simulations results

Crash cushion finite element model and LS-DYNA3D simulation

The characteristics and the behaviour of the proposed impact attenuating system have been evaluated with the LS-DYNA3D simulation of the TC 1.1.100 crash test (table 2), standardized by the European guidelines EN 1317-3. The restraint capacity, the decelerations reduction within the standard limits and the likely accident dynamics are considered for this evaluation.
The simulation involves the frontal impact of a light vehicle (900 kg) moving at 100 km/h against the attenuating system. The impacting vehicle model dimensions are shown in figure 13; the vehicle model was downloaded from the NCAC (FHWA/NHTSA National Crash Analysis Center) website and it is specific for frontal impacts simulations as it contains 16100 elements, opportunely joined in 208 parts.

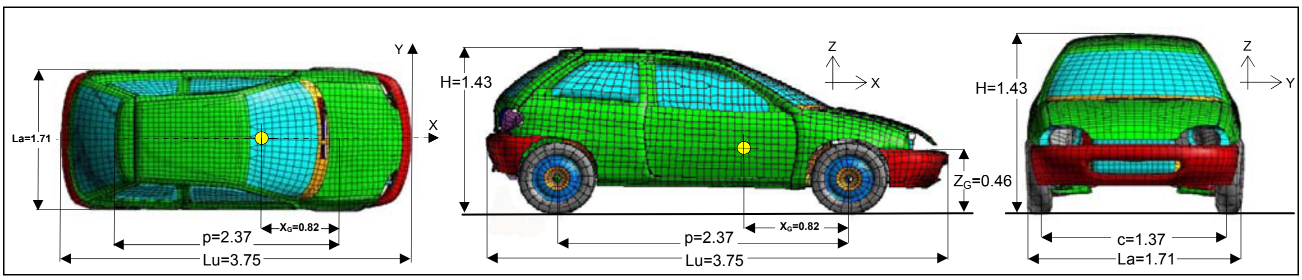


Figure 13: Geo Metro vehicle f. e. model (NCAC)

The features of the crash cushion model include (figures 14 and 15):

- a set of six stand-alone preformed modular attenuating elements (cushions) (figure 14.a and 15.b);
- a concrete base, opportunely profiled to place the cushions (figure 14.b);
- a frontal aluminium nose (figure 15.a);
- geosynthetics wrapping the modular elements.

The single cushion f.e. model dimensions are sketched in figure 14.a; each part is formed by 656 cubic 10 cm side brick elements.
Table 5 shows the input values adopted for the “Aggregate and Foam” material model parameters for the cushions LS-DYNA3D model. As the specimens tested in the laboratory phase seemed too stiff for attenuating purposes, the chosen values for the material model parameters have been consequently reduced. This reduction was estimated as function of an increased mixture air voids content, for producing cushions able to dissipate at least an impact energy of 320 kJ and respecting the maximum standard decelerations limits. This aim was achieved by increasing the nominal aggregate blend size from 8-10 mm to 10-12 mm and varying the volume percentage of aggregates in the mix. A new set of specimens have been produced and tested in the laboratory to asses whether the new modelled material could be actually obtained or not.

Table 5: Input parameters of Aggregate and Foam material model

Bulk density (kN/m^3)	Young’s modulus E (MPa)	Poisson’s ratio *v*	Shear modulus G (MPa)	Bulk modulus (MPa)			Yield stress (MPa)	Failure stress (MPa)
				K_1	K_2	K_3		
3.00	1.06	0.40	0.40	3.00	0.75	2.40	0.40	-0.10

Each modelled cushion weighs about 1.24 kN. Its shape and position inside the concrete base have been opportunely studied in order to:
- reduce the likelihood of cushion tipping over due to lateral impacts;
- guarantee a progressive longitudinal compression and sliding due to frontal impacts, avoiding the use of steel cables or guides.

By inserting the cushion into the concrete base guide, only 0.8 m of it are emerging from the pavement surface. The concrete base can be obtained by assembling several concrete elements embedded in the pavement during construction. Each element shape should be defined in order to minimize its weigh and to create a cavity into which cushions can slide without being tipped over in the event of lateral impacts. The modelled final concrete guide dimensions are reported in figure 14.b. Its length depends on the number of cushions adopted.

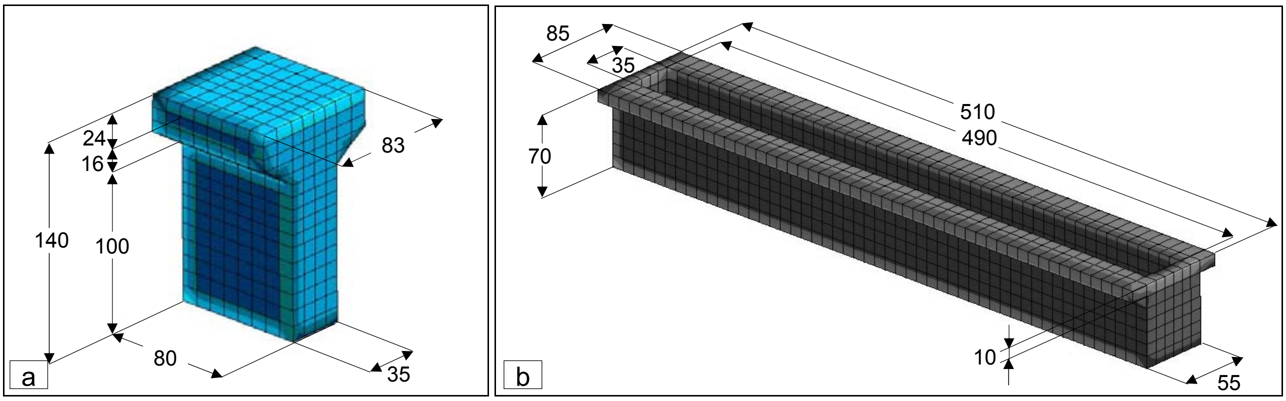


Figure 14: a) Cushion mesh, b) concrete base mesh

A frontal aluminium nose is positioned in front of the cushions with the aim of containing the initial decelerations of the impacting vehicles and allowing a progressive deformation of the system. It is modelled with aluminium shell elements 3 mm thick. The mesh is shown in figure 15.a, while the properties of the corresponding material model are reported in table 6.

Table 6: Input parameters of nose material and of nonwoven geosynthetic material

Element	Bulk density (kN/m^3)	Young’s modulus E (MPa)	Poisson’s ratio *v*	Failure plastic strain	Yield stress (MPa)
Nose (aluminium)	28.00	71000	0.33	0.20	230
Nonwoven geotexile	9.10	80	0.30	0.55	24

The model of the system has been completed by inserting a set of two geosynthetics wrapping the series cushions, with the purpose of reducing their shift during the impact and containing possible debris detaching from the system. The characteristics of the corresponding geosynthetic material model are shown in table 6.
Finally, a concrete bridge pile was modelled behind the attenuating system for reproducing a typical hazardous road singularity (figure 15.c).
The performance of the system, in terms of structural adequacy and after-collision vehicle trajectory, has been evaluated considering the kineto-dynamic behaviour of the elements during and after the impact. As

shown in figure 16, the simulation test displayed that the system has the capability to restrain the vehicle in safe conditions, with no-tip over risks. No parts of the attenuating system detached and penetrated the cockpit. Moderate yaw, rolling and pitching were registered in the vehicle. The after-collision vehicle trajectory did not interfere with other possible vehicles on the road.

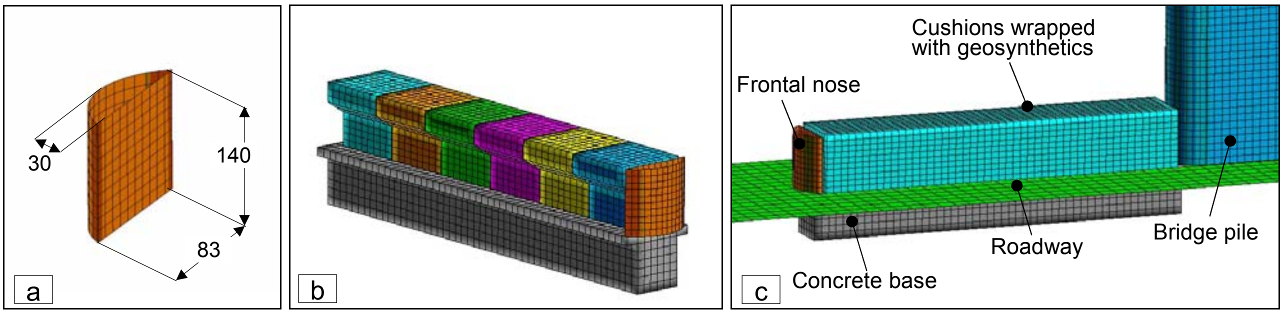


Figure 15: a) Nose mesh, b) cushion set mesh, c) attenuator f.e. model

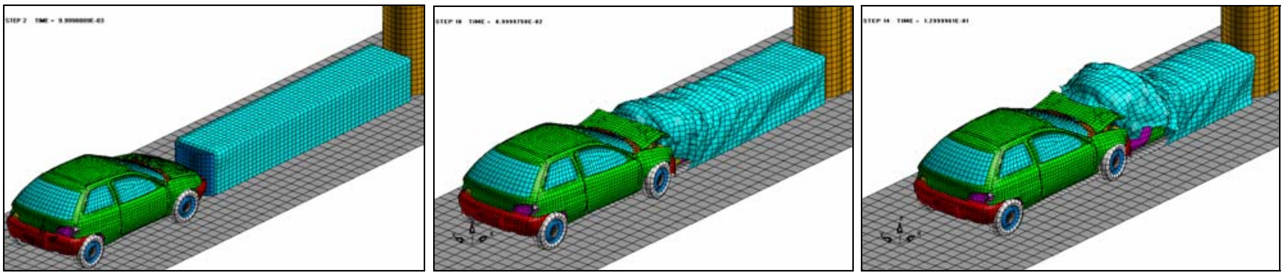


Figure 16: TC 1.1.100 test (EN 1317-3) simulation

The accident severity and occupant risks have been estimated with regard to ASI, THIV and PHD indexes calculated as here reported:

- ASI index worked out as a function of the maximum decelerations of the vehicle mass centre referred to the local coordinates system;
- THIV index worked out as a function of the speed of the theoretical occupant head when impacting one of the cockpit internal surfaces: this speed is computed on the xy plane of the local coordinates system;
- PHD index worked out as a function of the maximum post-impact theoretical occupant head accelerations calculated on a time step of 10 ms after the head-cockpit collision.

THIV and PHD indexes are related to the motion of the occupant head with reference to the vehicle. These indexes are indirectly worked out thanks either to the vehicle kinematic magnitudes referred to the global coordinates system and to the distance of the theoretical head from the origin of the baricentrical local coordinate system; in this way, as standards report, no accelerometers are needed close to the occupant theoretical head for indexes calculations.

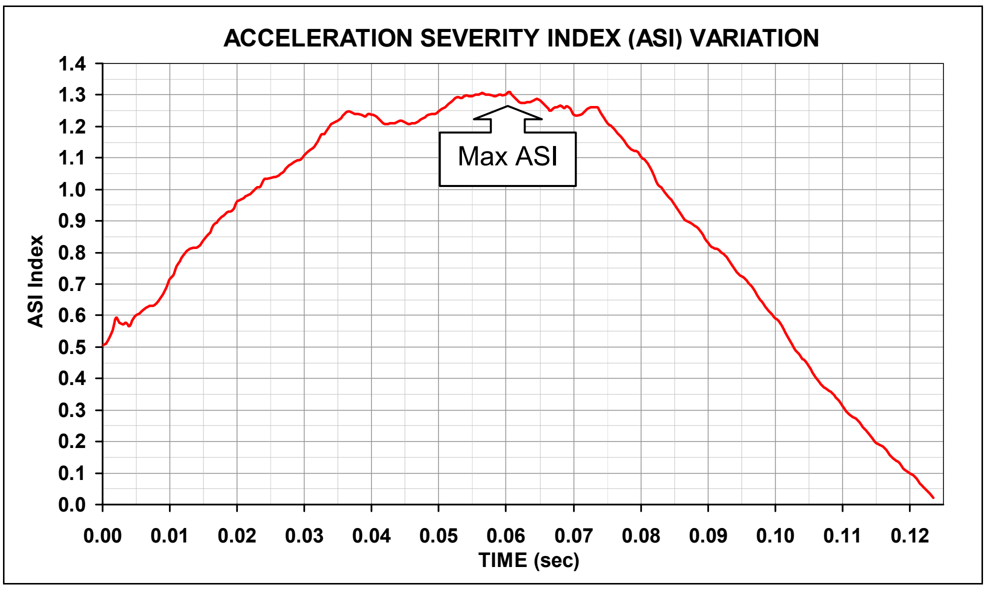


Figure 17: ASI versus Time Plot

Graphs reported in figure 17 plots the variation of the ASI value worked out through the first 0.12 seconds of event. In this period the maximum ASI value is obtained approximately at 0.06 seconds.
Table 7 shows the obtained results.

Table 7: Obtained values for references indexes

Reference index	EN 1317-3 specifications	Simulation results
ASI	≤ 1.4	1.31
THIV	≤ 44 km/h	25.56 km/h
PHD	≤ 20g	17.87g

CONCLUSIONS

Based upon the developed research work, the following concluding remarks can be stated:

- a new conception of road impact attenuator made with lightweight material is here proposed; it should be used for shielding narrow hazards and is characterised by low construction and repair costs if compared to other currently employed systems;
- the developed expanded clay mixture bonded with silicon resin can be easily produced at room temperature in opportunely profiled cases; compaction is not needed and setting is fast; the mixture is not affected by significant thermo-hygrometric volume variations and presents high dissipative properties, so that it can be successfully adopted for crash cushions;
- the cushions constituting the proposed attenuating system do not need special pieces of equipment for transporting and placing and can be easily substituted; their position in the concrete base reduces the probability of tipping over during lateral impacts and guarantees controlled sliding during frontal impacts;
- the developed attenuating system has potentially the capability to restrain a light vehicle impacting frontally at 100 km/h with no-tip over risks; during the performed simulations no parts of the attenuating system detached and penetrated in the cockpit;
- moderate yaw, rolling and pitching were registered in the vehicle; no deformations were registered concerning the cockpit; the after-collision vehicle trajectory did not interfere with other possible vehicles on the road;
- during the crash event, plastic deformations were recorded in the cushions, while the geosynthetics tore at the concrete base according to their containment function;
- the vehicle-impact simulation provided values for ASI, THIV and PHD indexes satisfying the EN 1317-3 specifications; the inertial forces occurred on occupants did not result capable to produce permanent injuries;

Future plans:

- new laboratory and in situ tests are being studied in order to validate the proposed system and its composing materials: a boogie vehicle or a scaled pendulum would be desirable for dynamic testing purposes;
- new materials are being considered, especially new binders, with the aim of enhancing the attenuating features of the cushions; in particular, to reduce ASI, THIV and PHD indexes values in frontal impacts and to evaluate the vehicle-attenuator system behaviour during lateral crash events;
- the cushions shape and the number of cushions within the system are being taken into account with regard to the costs of construction and maintenance and to the system redirective capabilities;
- the cushions wearing off due to varying environmental conditions (e.g. water and humidity, freeze and thaw, etc.) needs to be investigated;
- heavy truck and two-wheels vehicles crash tests simulations are planned.

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